

02R00380

**POLARISATION ROTATOR, PARALLAX BARRIER, DISPLAY AND
OPTICAL MODULATOR**

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION:

The present invention relates to a polarisation
5 rotator for rotating the plane of polarisation of linearly
polarised light by an arbitrary angle. Such a rotator may
be used, for example, as part of a parallax barrier in a
display or as an optical modulator in telecommunications.
The present invention also relates to parallax barriers,
10 displays and optical modulators including such polarisation
rotators.

2. DESCRIPTION OF THE RELATED ART:

A known type of liquid crystal device (LCD) is the
15 twisted nematic (TN) type. In such a device, a layer of
nematic liquid crystal material is disposed between opposing
alignment surfaces, such as rubbed polyimide, which cause
the liquid crystal director to twist through 90° from one
alignment surface to the other in the absence of an applied
20 field. In the absence of an applied field, the plane of
linearly polarised light passing through the device is
rotated by 90° .

A relatively low voltage, for example between 0 and
25 3 volts, is sufficient to switch such TN LCDs. When switched
to the non-rotating state, the mid-plane tilt angle of the

liquid crystal director rises above a predetermined angle such that the surface regions of the liquid crystal material adjacent the alignment surfaces may be considered as substantially decoupled voltage-dependent optical retarders. Each of these retarders may be represented by a single optic axis along the alignment direction of the alignment surface. The alignment directions of the opposing surfaces are orthogonal to each other so that, provided the pre-tilt of the liquid crystal molecules at the alignment surfaces are substantially equal, the retardations of the surface regions of the liquid crystal layer effectively cancel each other out so that the device provides substantially zero retardation. However, this self-compensation only occurs for twist angles of 90° .

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TN LCDs having twists other than 90° are also known. When linearly polarised light is passed through such devices, the polarisation is converted to elliptical polarisation. In order to switch such a device so as to have substantially no effect on the polarisation of light passing therethrough, a theoretically infinite voltage is required in order to reduce the retardation to zero.

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Beynon et al, Journal of the SID, 1999, 7, 71 disclose a technique for calculating linear to circular polarisation conversion in a TN LCD and apply the result to reflective

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displays comprising a liquid crystal spatial light modulator disposed between a reflector and a polariser.

SUMMARY OF THE INVENTION

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According to a first aspect of the invention, there is provided a polarisation rotator for rotating the polarisation direction of linearly polarised light by an angle γ different from 90° , comprising a layer of liquid crystal material disposed between a first input alignment surface and a second output alignment surface, the rotator having a mode in which a 90° twist of the liquid crystal director is induced across the layer, the layer having a retardation substantially given by:

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$$\tan\left[\pm\frac{\pi}{2}-\gamma\right] = \frac{\tan\left[\pm\frac{\pi}{2}\cdot\sqrt{1+\alpha^2}\right]}{\sqrt{1+\alpha^2}}$$

$$\alpha = \pm \frac{2 \cdot \Delta n \cdot d}{\lambda}$$

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$$2\theta = \gamma \mp \frac{\pi}{2}$$

where λ is a wavelength of light, Δn is the birefringence of the liquid crystal material, d is the thickness of the layer, and θ is the angle between the polarisation direction of input light and the alignment direction of the first alignment surface.

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λ may be a wavelength of visible light.

5 The rotator may have a further mode in which there
is substantially no twist of the liquid crystal director
across the layer.

10 The first and second alignment surfaces may induce
the 90° twist of the director across the layer.

15 The liquid crystal material may contain a chiral
dopant. The chiral dopant may induce the 90° degree twist
of the director across the layer.

20 The liquid crystal material may be a nematic liquid
crystal material of positive dielectric anisotropy.

25 The liquid crystal material may be a smectic liquid
crystal material.

30 The liquid crystal material may be a nematic liquid
crystal material of negative dielectric anisotropy.

35 The pretilts at the first and second alignment
surfaces may be substantially equal to each other.

The rotator may comprise an electrode arrangement for selectively applying a field across at least one region of the layer. The electrode arrangement may comprise an active or passive matrix.

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The rotator may comprise an input polariser having a transmission axis oriented at $-\theta$ to the alignment direction of the first alignment surface.

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The rotator may comprise an output polariser having a transmission axis substantially perpendicular to the polarisation direction of the input light.

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The rotator may comprise an output polariser having a transmission axis oriented at substantially $(\gamma \pm n.90)^\circ$ to the polarisation direction of the input light, where n is an integer.

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The absolute value of γ may be greater than or equal to 40° and may be less than or equal to 70° . γ may be equal to $\pm 45^\circ$ and $\Delta n.d/\lambda$ may be equal to 0.487. θ may be equal to $\mp 22.5^\circ$. As an alternative, θ may be equal to $\mp 12.5^\circ$.

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γ may be equal to $\pm 55^\circ$ and $\Delta n.d/\lambda$ may be equal to 0.55. θ may be equal to $\mp 17.5^\circ$.

The absolute value of γ may be greater than or equal to 175° and may be less than or equal to 180° . γ may be equal to 180° , θ may be equal to $\pm 45^\circ$ and $\Delta n \cdot d / \lambda$ may be equal to 1.414. As an alternative, γ may be equal to $\pm 178^\circ$,
5 θ may be equal to $\pm 44^\circ$ and $\Delta n \cdot d / \lambda$ may be equal to 0.105.

According to a second aspect of the invention, there is provided a parallax barrier comprising a rotator according to the first aspect of the invention.

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The barrier may comprise a patterned retarder, such as a halfwave retarder. The retarder may comprise first and second regions and γ may be equal to the included angle between the slow axes of the first and second regions. The
15 included angle may be between 40° and 70° . The slow axes of one of the first and second regions may be parallel or perpendicular to the polarisation direction of the input light. The slow axes of the other of the first and second regions may be oriented at 45° to the polarisation direction
20 of the input light. As an alternative, the slow axes of the other of the first and second regions may be oriented at 55° to the polarisation direction of the input light.

According to a third aspect of the invention, there
25 is provided a display comprising a rotator according to the

first aspect of the invention or a barrier according to the second aspect of the invention.

According to a fourth aspect of the invention, there
5 is provided an optical modulator comprising a rotator according to the first aspect of the invention.

It has been found that a TN LCD with a 90° twist
can be used to rotate the plane of polarisation of linearly
10 polarised light by any arbitrary angle. The effect may be modulated (between providing polarisation rotation and providing no polarisation rotation) by means of a relatively low finite voltage. Such a device has many applications, for example as part of a parallax barrier in a switchable
15 2D/autostereoscopic 3D display and as an optical modulator in an optical telecommunications system.

Throughout the present specification, positive values of angles may be either clockwise or anti-clockwise,
20 with negative values then referring to angles in the opposite direction. Also, all angles of polarisation directions and retarder slow axes are expressed "modulo 180° ". Thus, each angle β is equivalent to each angle $(\beta + n.180)^\circ$, where n is any integer. However, in some embodiments, because of
25 the nature of their constructions, a value of β may be

preferred over the value of $(\beta + 180^\circ)$ because of improved performance.

BRIEF DESCRIPTION OF THE DRAWINGS

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The invention will be further described, by way of example, with reference to the accompanying drawings, in which:

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Figure 1 is a graph of polarisation rotation against retardation;

Figure 2 is a diagram illustrating a polarisation rotator constituting a first embodiment of the invention;

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Figure 3 is a cross-sectional view of the rotator of Figure 2;

Figure 4 is a cross-sectional diagram illustrating the use of the rotator of Figure 2 as a display;

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Figure 5 is a cross-sectional diagram illustrating the use of the rotator of Figure 2 as part of a parallax barrier in a display which is switchable between a two dimensional (2D) mode and an autostereoscopic three dimensional (3D) mode;

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Figure 6 is a diagram illustrating part of the display shown in Figure 5;

5 Figure 7 is a diagram illustrating a polarisation rotator constituting a second embodiment of the invention;

Figure 8 is a diagram illustrating a modified part of the display shown in Figure 5;

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Figure 9 is a diagram illustrating a polarisation rotator constituting a third embodiment of the invention; and

15 Figure 10 is a diagram illustrating a polarisation rotator constituting a fourth embodiment of the invention.

Like reference numerals refer to like parts throughout the drawings.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is possible to derive conditions for which an LCD converts a first linear polarisation to any arbitrary
25 different linear polarisation of light, such as visible light, based on the technique disclosed by Beynon et al, Journal

of the SID 1999, 7, 71. By setting the twist angle ϕ to
 + or - 90° (+ or - $\pi/2$), the following condition relates
 the angle γ of rotation of the linear polarisation azimuth
 (with respect to the incident polarisation azimuth) to the
 5 retardation of a nematic liquid crystal layer:

$$\tan\left[\pm\frac{\pi}{2}-\gamma\right] = \frac{\tan\left[\pm\frac{\pi}{2}\cdot\sqrt{1+\alpha^2}\right]}{\sqrt{1+\alpha^2}}$$

$$\alpha = \pm \frac{2 \cdot \Delta n \cdot d}{\lambda}$$

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$$2\theta = \gamma \mp \frac{\pi}{2}$$

where d is the thickness of the layer, λ is the wavelength
 of light, Δn is the birefringence of the liquid crystal
 15 material, and θ is the angle between the azimuth of the
 incident linear polarisation and the input director of the
 liquid crystal. This is represented graphically in Figure
 1, which plots the rotation angle γ as a function of the
 retardation $\Delta n \cdot d / \lambda$ for the first three "branches" or
 20 solutions for positive values of γ . Negative values of γ
 may be obtained by reflecting the graph of Figure 1 about
 the x axis but, as a polarisation rotation of $+45^\circ$ is
 substantially identical to a polarisation rotation of -135° ,
 these curves have not been shown. The curves are periodic
 25 in positive or negative γ and the number of branches is infinite

in extent in terms of retardation. The crossing points for $\gamma = 90^\circ$ are the known Gooch-Tarry 90° TN minima.

The polarisation rotator shown in Figure 2 is arranged to provide a rotation of linear polarisation by 45° . The rotator comprises an input polariser 1 which receives unpolarised input light 2 and has a transmission axis 3 oriented vertically and defining a reference direction. As shown in Figure 3, the polariser 1 is formed on or attached to a first liquid crystal (LC) substrate 4 which, together with a second substrate 5, defines a cell containing a liquid crystal layer 6. The inner surfaces of the substrates 4 and 5 have formed thereon conductive transparent electrodes 7 and 8, for example made of indium tin oxide (ITO), and alignment layers 9 and 10, for example comprising rubbed polyimide layers. The rubbing directions of the alignment layers 9 and 10 are orthogonal to each other.

The alignment direction of the alignment layer 9 is illustrated at 11 in Figure 2 and is oriented at -22.5° with respect to the transmission axis 3. The alignment direction 12 of the alignment layer 10 is therefore oriented at $+67.5^\circ$ with respect to the transmission axis 3.

The liquid crystal material of the layer 6 is of nematic type and the alignment layers 9 and 10 induce, in

the absence of an applied field across the layer 6 between the electrodes 7 and 8, a -90° twist to the liquid crystal director from the alignment layer 9 to the alignment layer 10. The alignment layers are also such that the pre-tilts
5 at the surface regions of the layer 6 have substantially the same magnitude. A small amount of chiral dopant may be used to induce a (positive or negative) twist in the liquid crystal as desired.

10 The liquid crystal layer 6 has a retardation $\Delta n \cdot d / \lambda = 0.487$ and, in the absence of an electric field applied between the electrodes 7 and 8, the rotator rotates the plane of polarisation of the light from the polariser 1 by 45° as illustrated at 13 in Figure 2. When a sufficiently large
15 voltage, for example of the order of 3 volts, is applied between the electrodes 7 and 8 across the layer 6, the mid-plane tilt angle of the liquid crystal director in the middle region of the layer 6 rises to a value such that the surface regions of the layer 6 act as substantially decoupled
20 voltage dependent optical retarders. The optic (slow) axes of these regions are then effectively determined by the rubbing directions of the alignment layers 9 and 10 and so are orthogonal to each other. The retardations of these decoupled retarders thus cancel each other out and the device
25 has substantially no effect on the polarisation of light passing therethrough. In this state, the device passes the

vertically polarised light from the polariser 1 substantially without rotating or changing the polarisation state of the light.

5 As shown in Figure 4, a rotator of this type may be used as a pixellated liquid crystal display. The electrode 7 is divided into individual pixel electrodes, each of which is associated with a thin film transistor (TFT) 14 forming part of an active matrix addressing arrangement
10 of the display. Colour filters 15, such as red, green and blue filters, are formed on the substrate 5 in order to provide a colour display and an analysing polariser 16 is formed or disposed on the outer surface of the substrate 5. The transmission axis of the analysing polariser 16 is orthogonal
15 to the transmission axis of the polariser 1 so that, when a sufficient electric field is applied across a pixel, the analysing polariser 16 substantially extinguishes light passing through the pixel, which therefore appears in its dark or black state. When the applied field is removed,
20 the pixel rotates the plane of polarisation by 45° so that the polarisation plane is oriented at 45° with respect to the transmission axis of the analysing polariser 16. The pixel therefore appears in its bright or maximally transmissive state.

Figure 5 illustrates the use of the rotator in a display of the type disclosed in British patent application No. 0215059.7. The display comprises a backlight 20 disposed behind the input polariser 1 and a switching LCD in the form of the rotator shown in Figure 2. Light from the rotator passes to a patterned retarder 21 formed on a glass substrate 22. The patterned retarder 21 has first regions such as 23 for acting as parallax barrier slits and second regions such as 24 for acting as "opaque" barrier regions in the autostereoscopic 3D mode of the display.

The orientations of the various axes are shown in Figure 6. The transmission axis 3 of the polariser 1 is oriented at 45° . The alignment direction 11 of the alignment layer 9 is oriented at 22.5° . The alignment direction 12 of the alignment layer 10 is oriented at 112.5° . The regions 23 have slow axes 25 oriented at 90° whereas the regions 24 have slow axes 26 oriented at 45° . An analysing polariser 27 for the switching LCD has a transmission axis 28 oriented at 135° i.e. orthogonal to the transmission axis 3 of the input polariser 1.

The display further comprises a pixellated spatial light modulator (SLM) in the form of a "display LCD". The display LCD comprises a pixellated liquid crystal layer 30 disposed between substrates 31 and 32. Alignment layers,

electrodes, colour filters and addressing arrangements are not shown in Figure 5 for the sake of clarity. The analysing polariser 27 acts as an input polariser for the LCD and an output polariser 33 is provided on the outer surface of the substrate 32. The display LCD may be of any suitable type for displaying images.

In the 3D mode, the polarisation rotator is switched off by applying a voltage across the liquid crystal layer 6 so that no polarisation rotation takes place. Light from the polariser with the polarisation direction parallel to the transmission axis 3 passes through the rotator with its polarisation unchanged and likewise passes through the regions 24 with its polarisation unchanged. The transmission axis 28 of the analysing polariser 27 is perpendicular to the polarisation so that light passing through the regions 24 is substantially extinguished.

Light incident on the regions 23 is polarised at -45° with respect to the optic axis 25. The polarisation direction is rotated by 90° through the regions 23 so as to be aligned with the transmission axis 28 of the analysing polariser 27. The slits regions 23 thus appear substantially transparent so that the retarder 21 and associated elements act as a rear parallax barrier.

In the 2D mode, no field is applied across the liquid crystal layer 6. This layer therefore provides 45° of polarisation rotation so that the polarisation direction of light incident on the patterned retarder 21 is 90° . The regions 23 do not affect the polarisation direction whereas the regions 24 cause the polarisation to be rotated by -90° . Light from both the regions 23 and 24 therefore has polarisation directions oriented at 45° with respect to the transmission axis 28 of the analysing polariser 27, so that the display LCD receives light of substantially the same intensity from the regions 23 and 24. The barrier structure is therefore substantially invisible and the display operates in the 2D mode.

Figure 7 illustrates a modification to the arrangements shown in Figures 5 and 6 in order to provide an arrangement for use in the display disclosed in British patent application No. 0215058.9. In such a display, the brightness in the 2D mode is substantially increased at the expense of a smaller decrease in brightness of the bright state of the 3D mode. A polarisation rotation of 55° is required for such a display and the relevant orientations are illustrated in Figure 7. Thus, the alignment direction 11 is oriented at 27.5° , the alignment direction 12 is oriented at 117.5° , and the optic axis 25 is oriented at 100° . The other orientations are as shown in Figure 6. In

order to provide the 55° rotation, the retardation $\Delta n \cdot d / \lambda$ of the liquid crystal layer is 0.55.

Although an example with 55° of polarisation
5 rotation is illustrated in Figure 7, other rotations may
be provided as necessary according to the needs of the
particular example of the display.

In general, the required polarisation rotation angle
10 is the same as the included angle between the slow axes 25
and 26 of the retarder regions 23 and 24, respectively.

Figure 8 illustrates an arrangement which differs
from those shown in Figures 5 and 6 in that the orientation
15 and retardation are changed to optimise the output of the
patterned retarder 21 so as to achieve substantially
identical spectral responses from the regions 23 and 24 in
the 2D mode. The liquid crystal layer 6 has a retardation
 $\Delta n \cdot d / \lambda = 0.415$, the alignment direction 11 is oriented at 57.5° ,
20 and the alignment direction 12 is oriented at 147.5° .

Figure 9 illustrates a generic arrangement which
different from the arrangement of Figure 2 in that an output
polarising analyser 27 having a transmission axis 28 is
25 provided. The alignment direction 11 of the alignment layer
9 is oriented at an angle θ in either direction with respect

to the transmission axis 3 of the input polariser 1. The alignment direction 12 of the alignment layer 10 is orthogonal to the alignment direction 11. The output polarisation 13 is rotated by γ compared with the input polarisation 3' of light from the polariser 1 and the transmission axis 28 is oriented at $(\gamma \pm n.90)$ with respect to the transmission axis 3, where n is any integer (positive or negative or zero). Thus, the transmission axis 28 may be parallel to or orthogonal to the output polarisation 13 in the absence of an applied field across the liquid crystal layer 6.

Figure 10 illustrates an arrangement which differs from the arrangement of Figure 9 in that the transmission axis 28 of the analysing polariser 27 is oriented at $(\pm n.90)$ with respect to the transmission axis 3. Again, n may be any integer (positive or negative or zero). The transmission axis 28 may therefore be parallel to or orthogonal to the transmission axis 3.

The embodiments described hereinbefore use a layer of nematic liquid crystal material having positive dielectric anisotropy. In such embodiments, the alignment surfaces for the liquid crystal material provide relatively small pre-tilt angles whose azimuths are orthogonal to each other. In the absence of an applied field, there is a 90°

twist in the liquid crystal director from one alignment surface to the other.

Other liquid crystal modes may be used, for example
5 in the arrangements shown in the drawings, with modifications
as appropriate to the actual mode of operation. For example,
the liquid crystal material may comprise a nematic material
of negative dielectric anisotropy and the alignment surfaces
may be arranged to induce a substantially homeotropic
10 orientation of the liquid crystal director in the absence
of an applied field. The liquid crystal adjacent the
alignment surfaces has a high pre-tilt, for example close
to 90° . In the absence of an applied field, the homeotropic
alignment results in substantially no change to the
15 polarisation state of light passing through the layer.

When an electric field is applied across the layer
of such a material, the pre-tilt caused by the alignment
surface and/or a structure such as the electrode structure
20 below the alignment surface causes the liquid crystal
directors of the molecules near the alignment surfaces to
be reoriented in a predetermined direction. The liquid
crystal material may also include a chiral dopant whose
concentration may be such as to induce a pitch of twist in
25 the liquid crystal layer such that the ratio of the pitch
to the thickness of the layer is substantially equal to 0.25.

When an electric field greater than a predetermined voltage is applied across the layer, the layer takes up a substantially 90° twist. Thus, in such embodiments, the polarisation rotator is active in the presence of an applied field and is inactive in the absence of an applied field.

It is also possible to provide embodiments in which the liquid crystal material is of the smectic type.

A polarisation rotator of the type shown in Figure 2 may be used in other applications, one example of which is as an optical modulator, for example in telecommunication applications. For example, the rotator may be used to provide a π phase modulator by selectively providing a polarisation rotation of 180°, which is equivalent to inducing a π phase lag in linearly polarised light. In order to produce a 180° polarisation rotation, the retardation $\Delta n \cdot d / \lambda$ of the liquid crystal layer may be made 1.414 and the angle between the azimuth of the incident linear polarisation and the input director of the liquid crystal may be made 45°. The phase change provided by the modulator may be controlled by a relatively low modulating voltage, for example about 3 volts, which is compatible with CMOS technology.

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As an alternative, a polarisation rotation close

to 180° may be used to achieve almost the same effect. For example, a rotation of 178° may be achieved with $\Delta n \cdot d / \lambda = 0.105$ and $\theta = 44^\circ$. Such a low retardation allows the use of a very thin liquid crystal layer which, in turn, provides a very rapid response time. This is advantageous in telecommunication applications, where fast switching is very desirable.

Various other modifications will be apparent to and can be readily made by those skilled in the art without departing from the scope and spirit of this invention. Accordingly, it is not intended that the scope of the claims appended hereto be limited to the description as set forth herein, but rather that the claims be broadly construed.